

Relationship between Soil Test Phosphorus and Phosphorus in Runoff: Effects of Soil Series Variability

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ABSTRACT

Phosphorus loss in runoff from agricultural fields has been identified as an important contributor to eutrophication. The objective of this research was to determine the relationship between phosphorus (P) in runoff from a benchmark soil (Cecil sandy loam; fine, kaolinitic, thermic Typic Kanhapludult) and Mehlich III-, deionized water-, and Fe_2O_3 -extractable soil P, and degree of phosphorus saturation (DPS). Additionally, the value of including other soil properties in P loss prediction equations was evaluated. Simulated rainfall was applied (75 mm h^{-1}) to 54 1-m^2 plots installed on six fields with different soil test phosphorus (STP) levels. Runoff was collected in its entirety for 30 min and analyzed for total P and dissolved reactive phosphorus (DRP). Soil samples were collected from 0- to 2-, 0- to 5-, and 0- to 10-cm depths. The strongest correlation for total P and DRP occurred with DPS ($r^2 = 0.72$). Normalizing DRP by runoff depth resulted in improved correlation with deionized water-extractable P for the 0- to 10-cm sampling depth ($r^2 = 0.81$). The STP levels were not different among sampling depths and analysis of the regression equations revealed that soil sampling depth had no effect on the relationship between STP and P in runoff. For all forms of P in runoff and STP measures, the relationship between STP and runoff P was much stronger when the data were split into groups based on the ratio of oxalate-extractable Fe to Al. For all forms of P in runoff and all STP methods, R^2 increased with the inclusion of oxalate-extractable Al and Fe in the regression equation. The results of this study indicate that inclusion of site-specific information about soil Al and Fe content can improve the relationship between STP and runoff P.

OVER THE PAST DECADE, controlling nonpoint-source pollution has come to the forefront in efforts to improve water quality. The principal components of agricultural nonpoint-source pollution are sediment, bacteria, and nutrients such as N and P. Of these, P is the element most commonly associated with eutrophication in freshwater systems because these systems are usually P-limited (Correll, 1998).

Phosphorus has been considered relatively immobile in soil because the rates of fertilizer P application are commonly low compared with the soil sink for P. However, there is probably a limit to this sink and after long-term overapplication of P, levels may build beyond the soil's P fixing capacity. When this happens, P that is applied to the land in fertilizer or animal manure may be lost to the surrounding environment. In areas of concentrated livestock production, land application of

large volumes of manure, enriched with imported nutrients, is commonplace.

Soils with high STP levels can contribute significant amounts of P to runoff as dissolved P or particulate-bound P (Pote et al., 1999b; Sharpley, 1995). The relationship between STP and P in runoff has been shown to be soil-specific (Sharpley, 1995), and therefore it is difficult to assign universally acceptable STP values above which P loss is unacceptable. Additionally, there are currently no federal standards for P levels in surface waters, although ambient water quality criteria have been recommended recently by the USEPA.

Forms of P in runoff can include dissolved P in organic and inorganic forms as well as particulate-bound P associated with mineral or organic sediments. Because erosion rates from hayfields and pastures are low, dissolved P is usually the dominant form of P in hayfield and pasture runoff (Sharpley et al., 1992). Dissolved P in runoff results from the interaction of rainwater with the soil's surface. The effective depth of the interaction between soil and runoff is dependent on soil aggregation, percent ground cover, slope, and rainfall intensity (Sharpley, 1985). In two studies on effective depth of interaction using soil sieved to 2 mm, this depth ranged from 0.2 cm to more than 3.7 cm depending not only on the factors mentioned above but also on the experimental method used (Sharpley et al., 1981; Sharpley, 1985).

Chemical extractants that simulate soil P availability have been used for decades to predict crop yield response to added P in fertilizer. According to Gartley and Sims (1994), the most common routine soil tests currently in use in the United States include Bray and Kurtz, Mehlich I, Mehlich III, Morgan, modified Morgan, and Olsen P. Traditional interpretations of these tests as predictors of plant-available P are based on extensive research, but there are less data to support interpretations of potential environmental effects of soils that test high in P. Additionally, most soil samples submitted for agronomic testing are collected from a depth of 0 to 15 cm, but research has shown that P accumulates at the soil's surface as a result of long-term manure application. Phosphorus levels in the upper 2 cm of no-till fields may be three times higher than at 8 cm (Guertal et al., 1991).

Estimates of the strength of the relationship between STP and P in runoff range from $r^2 = 0.05$ to 0.94 (Table 1). All reported relationships in Table 1 were based on runoff from small ($<9 \text{ m}^2$) grassed plots under simulated rainfall. These studies covered a wide range

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Abbreviations: Al_{ox} , oxalate-extractable aluminum; DPS, degree of phosphorus saturation; DRP, dissolved reactive phosphorus; Fe_{ox} , oxalate-extractable iron; P_{ox} , oxalate-extractable phosphorus; STP, soil test phosphorus.

Table 1. Relationship between soil test phosphorus (STP, mg kg⁻¹) and dissolved reactive phosphorus (DRP, mg L⁻¹) in runoff as reported in the literature.

Reference	Soil series	Subgroup	Time since last manure application	STP method	Soil depth [†]	Regression slope	Regression intercept	Coefficient of determination (<i>r</i> ²)
			mo		cm			
Pote et al. (1999a)	Captina	Typic Fragiudult	48	Mehlich III	0–2	0.0022	0.255	0.65
Pote et al. (1996)	Captina	Typic Fragiudult	12	Mehlich III	0–2	0.0026	0.3	0.72
Daniel et al. (1993)	Captina	Typic Fragiudult	120	Mehlich III	0–5	0.003	0.513	0.05
Pote et al. (1999b)	Nella	Typic Paleudult	approximately 12‡	Mehlich III	0–2	0.0036	–0.45	0.82
Pote et al. (1999b)	Linker	Typic Hapludult	approximately 12‡	Mehlich III	0–2	0.0035	–0.38	0.84
Pote et al. (1999b)	Noark	Typic Paleudult	approximately 12‡	Mehlich III	0–2	0.0016	0	0.87
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	Mehlich III	0–2.5	0.005132	0.3433	0.62
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	Mehlich III	0–5	0.005189	0.3003	0.94
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	Mehlich III	0–15	0.007121	0.4811	0.41
Pote et al. (1999a)	Captina	Typic Fragiudult	48	deionized water	0–2	0.018	0.087	0.67
Pote et al. (1996)	Captina	Typic Fragiudult	12	deionized water	0–2	0.0118	0.1	0.82
Pote et al. (1999b)	Nella	Typic Paleudult	approximately 12‡	deionized water	0–2	0.0107	–0.18	0.85
Pote et al. (1999b)	Linker	Typic Hapludult	approximately 12‡	deionized water	0–2	0.0104	–0.11	0.86
Pote et al. (1999b)	Noark	Typic Paleudult	approximately 12‡	deionized water	0–2	0.0055	–0.03	0.94
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	deionized water	0–2.5	0.02695	0.1000	0.95
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	deionized water	0–5	0.02881	0.0727	0.96
Torbert et al. (2002)	Windthorst	Udic Paleustalf	6	deionized water	0–15	0.02906	0.3712	0.81

[†] Soil sampling depth for STP determination.

[‡] Some plots received manure within the year preceding runoff simulation.

of soil types, STP methods, and soil sampling depths, and the reported regression slopes and intercepts are quite different as a result. However, even when the sampling depth and extractants are the same (Pote et al., 1999b), there are still differences in slope and intercept values among soil series (i.e., Nella, Linker, and Noark). This seems to support the conclusions of Sharpley (1995) that the relationship between STP and P in runoff is soil-type-dependent. For the most part, reported coefficients of determination (Table 1) exceeded 0.60, the exception being Daniel et al. (1993), who reported no relationship between Mehlich III–extractable P and DRP in runoff ($r^2 = 0.05$). One difference between the study conducted by Daniel et al. (1993) and other studies listed in Table 1 is that plots used by Daniel et al. (1993) had not received P inputs for 10 yr whereas in most of the other studies some form of P (either inorganic or organic) had been applied to plots within 2 yr preceding the experiments. This suggests that the timing of manure applications may have an effect on the relationship between STP and P in runoff. Eghball et al. (2002) reported no relationship between STP and P in runoff when samples were collected immediately following manure application but a strong relationship a year after manure application. Furthermore, Pierson et al. (2001) observed that the relationship between STP and DRP in runoff was dependent on how much time had passed since the last litter application. These studies suggest that, as unincorporated manure reacts with the soil for some period of time, P in the manure becomes more closely associated with the soil at the surface so that it can then be more accurately represented by a soil test.

The biggest difference in reported regression equations seems to be the value of the intercept. The fact that some intercepts are positive and some are negative suggests that the STP method in question either extracted more P than runoff water (negative intercept) or less P than runoff water (positive intercept). This effect is probably due to soil-specific factors that regulate the interaction between runoff and the soil surface

and to P contributions leached from plant materials and residues on the soil surface. Another implication of these studies is that they seem to support the concept that sampling depth has a direct effect on the relationship between STP and P in runoff since there seems to be an inverse relationship between sampling depth and r^2 (Table 1). Torbert et al. (2002) reported that the strength of the relationship between STP and P in runoff was significantly reduced when sampling depth increased from 0 to 5 cm to 0 to 15 cm.

The objectives of this research were to determine the relationship between P concentration in runoff from a Cecil sandy loam, and four different measures of extractable soil P in samples collected over three different depths in six pastures and hayfields where STP levels had not been manipulated to achieve a predetermined range of STP values by the addition of manure. Additionally, we evaluated the effect of soil variability on this relationship and determined if the inclusion of other site-specific soil properties in addition to STP would improve P loss prediction.

MATERIALS AND METHODS

Experiments were conducted on soils of felsic igneous and metamorphic parent materials from the Piedmont region of Georgia. The benchmark soils chosen for this study are fine, kaolinitic, thermic Typic Kanhapludults (Cecil and Madison series). The well-drained Cecil soil comprises 14.7% of all soils mapped in the Piedmont (Radcliffe and West, 2003). The Madison series was included in this study because it differs from the Cecil only in solum thickness and it is often mapped in the same field with Cecil soils. The Madison series comprises 5.5% of the Piedmont area mapped (Radcliffe and West, 2003).

Six sites in the Piedmont region of northeastern Georgia were selected based on the following criteria: (i) Cecil and/or Madison soils present; (ii) fields managed for hay or pasture production; (iii) Mehlich-III STP level covering a range from low (10 mg kg⁻¹) to very high (>400 mg kg⁻¹); and (iv) no manure application in the previous 12 mo to eliminate fresh manure as a source of P that might not be reflected in STP.

To verify the presence of the soils series shown on the county surveys, hand-auger samples were taken to a depth of 100 cm at each field site. Owners and/or operators of fields used in this study verified manure application history verbally.

Following site selection, plot areas were mowed to a uniform (10-cm) height and raked free of clippings one week before the initial rainfall simulation. Plots were presoaked 24 h before the first simulated rainfall event via a drip-irrigation system with approximately 400 L of water to standardize antecedent soil moisture levels and reduce time to runoff. Paired 1- × 1-m plots, which were treated as pseudo-replicates, were installed at three side-slope positions within each site (upper, middle, and lower). Plot borders consisting of approximately 0.3-cm-thick sheet metal (15 cm tall) were pressed into the ground to a depth of at least 7 cm to isolate runoff. Aluminum flumes were installed at the down-slope edge of each plot to collect runoff.

A total of 54 rainfall simulations (three rainfall events × six plots × six fields) were conducted in this study. The rainfall scheme consisted of three rainfall simulations at 48-h intervals at each of the six sites. Cassel and Nielsen (1986) reported that a 48-h delay between rainfall events was sufficient time for soil to return to field capacity.

Simulated rainfall was applied to each pair of plots with a standard rainfall simulator and experimental protocol (Humphry et al., 2002). Local well water was used as the water source for the simulator and rainfall was applied at a rate of 75 mm h⁻¹ (range of 65 to 85 mm h⁻¹, standard deviation of 3.2 mm h⁻¹) to allow comparison of runoff between the six sites.

Collection of runoff began after continuous runoff commenced and continued for 30 min. Runoff was collected in its entirety and a 500-mL composite sample was taken and immediately placed on ice. Total runoff volume was recorded and a source water sample taken. In the lab, 125 mL of each runoff sample was filtered (0.45-μm pore diameter) to remove particulate matter. All samples were acidified with concentrated HCl and stored at -20°C until analyzed.

Composite soil samples consisting of 10 subsamples (2.5-cm diameter) were collected from each plot in depth increments of 0 to 2 cm, 0 to 5 cm, and 0 to 10 cm immediately after the third simulated rainfall application. The 0- to 2- and 0- to 5-cm depths were chosen because they correspond with sampling depths reported in previous research (Table 1). We included the 0- to 10-cm sampling depth because it is the depth recommended by the University of Georgia Soil Testing Laboratory for soil samples collected from hayfields or pastures. Soil samples were air-dried, ground, and sieved to 2 mm to remove large rock fragments and most of the grass thatch material. Soil pH was determined in a 1:2 soil to water mixture using a glass electrode, and particle size distribution was determined by the pipette method (Kilmer and Alexander, 1949). Extractable P in each soil sample was determined using three different methods: Mehlich III (Mehlich, 1984), Fe₂O₃ paper circles (Myers et al., 1997), and deionized water (Pote et al., 1996). Oxalate-extractable phosphorus (P_{ox}), iron (Fe_{ox}), and aluminum (Al_{ox}) were determined by inductively coupled plasma-mass spectroscopy. Degree of phosphorus saturation (DPS) was calculated as P_{ox} (mmol kg⁻¹) divided by Fe_{ox} and Al_{ox} and multiplied by 200 (Schoumans, 2000). Total carbon content was determined by combustion in a LECO (St. Joseph, MI) carbon, nitrogen, and sulfur analyzer.

Total P for all unfiltered runoff samples was determined colorimetrically (Murphy and Riley, 1962) following Kjeldahl digestion according to USEPA Method 351.2 (USEPA, 1979). Dissolved reactive P for filtered runoff samples was also determined colorimetrically (Murphy and Riley, 1962).

The overall flow-weighted concentration of each form of

P in runoff was calculated as the sum of the P concentration in runoff from each runoff event multiplied by the event runoff volume. This sum was then divided by the total runoff volume from the three runoff events. Both single-event P concentration and flow-weighted P concentration were regressed against each measure of STP for each sampling depth. The regression equations produced were not significantly different; therefore, only the relationship between STP and overall flow-weighted runoff P concentration will be discussed in this paper. Stepwise multiple regression, with a 0.20 significance level for entry, was also employed to determine if including oxalate-extractable Fe, Al, pH, sand, clay, and total carbon content, landscape, slope, and runoff volume would improve the ability to predict P levels in runoff. Analysis of variance was applied to runoff P and soil P. Statistical analyses were performed using the SAS software (SAS Institute, 1987).

The principle of conditional error (Bose, 1949; Milliken and Johnson, 1984) was used to evaluate regression equations relating STP to P in runoff. This is a technique for obtaining the sum of squares due to deviations from a hypothesis for linear models. The null hypothesis first tested was that one equation could be used to describe total P and DRP in runoff versus STP. This procedure provided an estimate of the residual sum of squares for the null hypothesis. Second, the alternative hypothesis that a separate equation was needed for each relationship was tested. The addition of the residual sum of squares for each separate equation provided an estimate of the residual sum of squares for the alternative hypothesis. The difference between the residual sum of squares of the null and alternative hypotheses provided an estimate of the residual sum of squares due to deviations from the null hypothesis. This residual sum of squares was then used in an *F* test against the residual sum of squares of the alternative hypothesis to determine if the relationships of total P and DRP with STP were significantly different.

RESULTS AND DISCUSSION

Site Characteristics

The presence of Cecil and/or Madison soils in each of the six fields was confirmed by direct observation of hand-augured soil profiles. Selected characteristics of the surface horizon at each site are listed in Table 2. Although there were significant differences in surface soil properties among the six sites, values for pH, total C, sand, and clay were within ranges described for soils identified as belonging to the Cecil series (Perkins, 1987; USDA Natural Resources Conservation Service, 2003).

The ranges of STP and DPS for plots and each sampling depth are shown in Table 3. Although there are fields with Mehlich-III levels in excess of 1000 mg kg⁻¹ in the Piedmont region of Georgia, the range of STP values for the plots in this study probably represent typical values. Additionally, the desire to avoid recently applied manure effectively precluded the use of fields with Mehlich-III levels exceeding 450 mg kg⁻¹. Deionized water and Fe₂O₃ paper extracted less P than Mehlich III. Also, deionized water- and Fe₂O₃ paper-extractable P were strongly correlated ($r^2 = 0.86$) and not significantly different ($p < 0.01$). The fact that there was no difference between the deionized water- and Fe₂O₃ paper-extractable P indicates that the soils in this study did not contain much weakly adsorbed P. Additionally, there was a strong relationship ($r^2 = 0.87$)

Table 2. Selected characteristics of the surface 10 cm of the six sites studied and the Cecil series.

Site	pH		Total C		Sand		Clay		Al _{ox} [‡]	Fe _{ox} [‡]
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
	g kg ⁻¹								mg kg ⁻¹	
1	5.0b†	0.1	2.3bcd	0.2	49.1d	12.3	24.1a	9.5	944abc	837b
2	5.4a	0.2	2.6cb	0.3	67.1ab	2.6	10.3b	2.9	690bc	756b
3	5.0b	0.1	2.1cd	0.4	55.5cd	6.6	20.3a	6.2	1058a	1170ab
4	4.8b	0.5	2.6b	0.4	47.8d	5.5	23.7a	7.9	847abc	1450a
5	5.7a	0.3	3.2a	0.5	71.2a	4.2	5.9b	1.2	983ab	1030ab
6	5.5a	0.3	1.9d	0.6	60.3bc	13.6	19.0a	12.1	619c	854b
Cecil§	4.1–6.5		0.6–3.4¶		8.7–78.7		6.2–41.9			

† Means followed by the same letter are not significantly different ($p < 0.05$).‡ Al_{ox}, oxalate-extractable aluminum; Fe_{ox}, oxalate-extractable iron.

§ Range of selected properties for Cecil soils as described by Perkins (1987) and USDA Natural Resources Conservation Service (2003).

¶ Organic carbon.

between Mehlich III-extractable P and both deionized water- and Fe₂O₃ paper-extractable P. The strong relationships among different STP methods suggest that they are extracting P from the same soil P pools and should exhibit a similar relationship with P in runoff.

Overall, sampling depth significantly affected STP for the deionized water and Fe₂O₃ paper extraction methods but not for Mehlich III or DPS. For the Fe₂O₃ paper-extractable P, all sampling depths were significantly different (based on Duncan's multiple range test following log-transformation). However, for the deionized water-extractable P, the 0- to 2-cm depth was different from the 0- to 10-cm depth, but the 0- to 2-cm samples were not different from the 0- to 5-cm samples, and the 0- to 5-cm samples were not different from the 0- to 10-cm samples (Table 3). There were no overall differences in Mehlich-III P or DPS among the three sampling depths. Other than the slightly higher deionized water- and Fe₂O₃ paper-extractable P concentrations in the 0- to 2-cm samples, there were no dramatic decreases in STP level with soil depth. It should be noted, however, that there was a slight trend toward increased extractable P in the 0- to 2-cm samples from some of the highest P sites. The fact that a dramatic buildup of P in the 0- to 2-cm samples was not observed probably indicates that over time, surface-applied P has moved downward in these soils. The downward movement of P in these soils is not very surprising given that the average sand content of the top 10 cm was 60%. In fact, there was no significant difference in DPS across the three sampling depths. Although the field sites chosen for this study had all received surface applied poultry manure (some for more than 30 yr), none of the sites had received manure over the preceding 12 mo and some of the sites may not have received manure for several years.

Phosphorus in Runoff versus Soil Test Phosphorus

Source water was analyzed for total P and ranged from 0.012 to 0.094 mg L⁻¹, with a mean of 0.04 mg L⁻¹. To eliminate this variability from data analyses, initial source water P concentration was subtracted from runoff total P and DRP concentrations.

Total P in runoff ranged from 0.42 to 1.25 mg L⁻¹, and DRP ranged from 0.15 to 0.80 mg L⁻¹. There was significant particulate-bound P in runoff and the ratio of DRP to total P ranged from 10 to 77% with a mean of 52%. The lowest STP plots showed the lowest ratio of DRP to total P. There was more variability in the concentration of DRP than total P, with the coefficient of variation (CV) of DRP ranging from 33 to 114%, and CV of total P ranging from 17 to 40%.

The relationships between each STP method and flow-weighted DRP in runoff (Fig. 1) are summarized in Table 4. Positive relationships were found between DRP and all soil P test methods. Similar to Pote et al. (1996, 1999a, 1999b), we found that in most instances DPS showed the strongest correlation to DRP in runoff, especially within a given sampling depth. This relationship was strongest for the 0- to 10-cm sampling depth ($r^2 = 0.70$). It is important to note, however, that DRP and Mehlich-III P, at the 0- to 5-cm depth, were also strongly correlated ($r^2 = 0.64$). With the exception of DPS, the strongest correlations between STP and runoff DRP were observed for soil samples collected from the 0- to 5-cm depth. Similarly, Torbert et al. (2002) reported that DRP in runoff showed the greatest correlation with Mehlich III- and deionized water-extractable P when soil samples were collected from the 0- to 5-cm depth. Torbert et al. (2002) related this effect to

Table 3. Phosphorus extracted from soil samples collected over three depth ranges by different soil test phosphorus (STP) methods and the degree of phosphorus saturation (DPS).

Depth	STP method											
	Mehlich III			Deionized water			Fe ₂ O ₃ paper			DPS		
	STP range	Mean	CV	STP range	Mean	CV	STP range	Mean	CV	STP range	Mean	CV
	mg kg ⁻¹											
cm												
0–2	32–460	148a‡	80	4–67	24a	81	10–86	32a	68	14–102	45a	65
0–5	28–403	134a	78	4–59	19ab	84	6–62	23b	70	10–90	39a	67
0–10	31–357	120a	81	4–56	15b	85	4–61	17c	83	5–97	35a	81

† Mean values followed by the same letter in a column are not statistically different ($p = 0.05$).

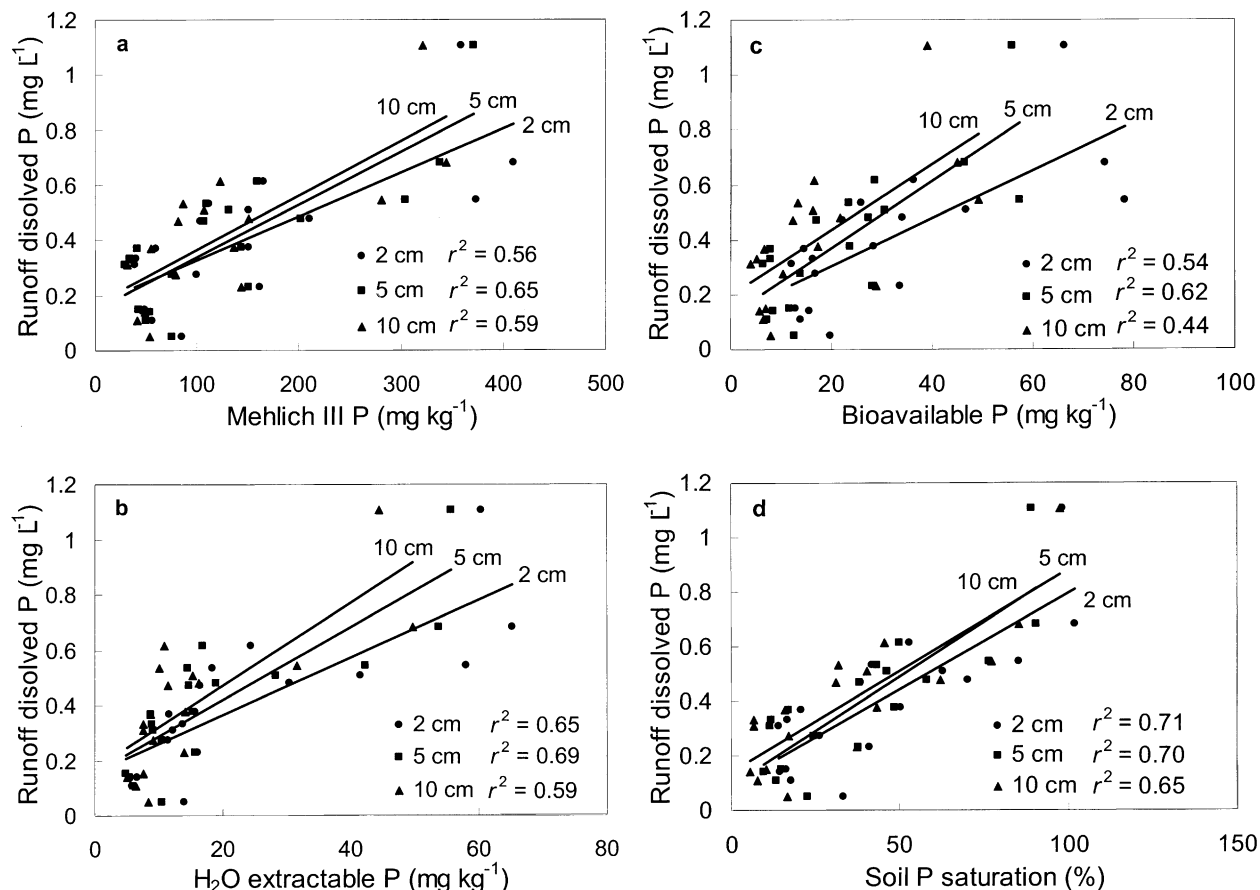


Fig. 1. Relationship between dissolved reactive phosphorus (DRP) in runoff and four measures of soil P (Mehlich III, deionized water, Fe₂O₃ paper, and degree of phosphorus saturation [DPS]) from samples collected over three depths (0–2, 0–5, and 0–10 cm).

increased variability in the 0- to 2-cm samples (Table 3), however we did not witness greater variability in STP in the 0- to 2-cm samples. We did find more variability in extractable P at the sites with highest STP levels. In fact, there were two plots at the highest STP site that had much larger differences in STP between the 0- to 2- and 0- to 5-cm sampling depths than any other plots in the study. The increased variability and possible buildup of P in the 0- to 2-cm samples at the highest P sites was probably related to more frequent and recent manure applications on these fields.

There was little difference among intercepts of the equations for DRP versus STP, but the value of the slope was different among STP methods. The difference in the slope values among the STP methods reflects their different P extracting abilities. As the P extracting strength of the STP method increases the slope of the line decreases. The positive intercept values imply that if STP were zero, there would still be significant DRP in runoff from these soils. This indicates that, in this study, there may have been a source of DRP that was not accounted for by the soil test. This source was most likely organic matter on the soil surface in the form of thatch and/or standing plant material both living and dead (Timmons et al., 1970; Sharpley, 1981). In fact Sharpley (1981) reported that P leached from the plant canopy accounted for between 18 and 94% of P lost in

runoff from bare soil. Additionally, Timmons et al. (1970) showed that dried grass residue could produce P losses of up to 0.3 kg ha⁻¹. In either case it is unlikely that these sources of P would be accounted for by a soil test. The difference in the value of the slope of the regression lines in the present study is mainly a function of the differences in the amount of P extracted by the different STP methods. This can be seen in Table 1 where the slope values for the two STP methods are similar across all the soil types listed but different between the two extractants.

While the relationship between STP and DRP in runoff is much more often reported in the literature, the relationship between STP and total P in runoff has been reported in only two studies of which we are aware (Andraski et al., 2003; Sharpley et al., 1992). Because the ratio of DRP to total P varied significantly in this study (0.10–0.70), the relationship between STP and total P was analyzed. As with DRP, there were strong relationships between runoff total P and all soil P measures (Fig. 2, Table 4). Similar to the relationships found with DRP, the strongest relationship between total P in runoff and STP ($r^2 = 0.72$) occurred with DPS for the 0- to 10-cm sampling depth. However, as with the DRP relationships reported above, the strongest relationships ($r^2 = 0.69$) between total P and STP measures were commonly associated with the 0- to 5-cm sampling

Table 4. Predictive equations and statistical parameters for the relationship between extractable soil P (mg kg⁻¹) and form of P in runoff.

STP [†] method	Depth	Intercept	Slope	r ²	RMSE	P > F	n
	cm	Relationship with runoff dissolved reactive phosphorus (DRP, mg L ⁻¹)					
Mehlich III	0–2	0.15	0.0017	0.56	0.1794	0.0004	18
	0–5	0.13	0.0020	0.64	0.1612	<0.0001	18
	0–10	0.15	0.0020	0.58	0.1747	0.0002	18
Deionized water	0–2	0.14	0.0108	0.65	0.1604	<0.0001	18
	0–5	0.14	0.0136	0.68	0.1525	<0.0001	18
	0–10	0.16	0.0153	0.58	0.1746	0.0002	18
Fe ₂ O ₃	0–2	0.11	0.0090	0.54	0.1819	0.0005	18
	0–5	0.11	0.0126	0.61	0.1683	0.0001	18
	0–10	0.18	0.0123	0.44	0.2019	0.0028	18
DPS [‡]	0–2	0.073	0.0073	0.65	0.1595	<0.0001	18
	0–5	0.076	0.0083	0.69	0.1498	<0.0001	18
	0–10	0.128	0.0076	0.70	0.1475	<0.0001	18
		Relationship with runoff total P (mg L ⁻¹)					
Mehlich III	0–2	0.43	0.0020	0.58	0.2129	0.0003	18
	0–5	0.40	0.0025	0.69	0.1834	<0.0001	18
	0–10	0.44	0.0025	0.58	0.2115	0.0002	18
Deionized water	0–2	0.42	0.0131	0.64	0.1958	<0.0001	18
	0–5	0.42	0.0165	0.68	0.1853	<0.0001	18
	0–10	0.46	0.0180	0.55	0.2199	0.0004	18
Fe ₂ O ₃	0–2	0.38	0.0112	0.58	0.2129	0.0003	18
	0–5	0.36	0.0162	0.69	0.1828	<0.0001	18
	0–10	0.47	0.0155	0.48	0.2364	0.0015	18
DPS	0–2	0.34	0.0089	0.66	0.1902	<0.0001	18
	0–5	0.35	0.0100	0.69	0.1827	<0.0001	18
	0–10	0.40	0.0090	0.72	0.1722	<0.0001	18

[†] Soil test phosphorus.[‡] Degree of phosphorus saturation.

depth. The slope of the STP versus total P equations showed the same differences due to STP method as the STP versus DRP equations. The intercept values for these equations were similar across STP methods, as was the case with DRP. The fact that the intercepts were positive, as with DRP, indicates that there may have been a source of total P in this study not accounted for by the soil tests. Furthermore, the positive intercepts point to surface OM as the source of the unaccounted-for total P because it is the only source of total P that would not have been accounted for by the soil tests.

The high degree of variability in DRP (CV = 33–114) may be attributed to the variability of runoff volume. Runoff from each plot ranged from 0.09 to 37.5 mm in 30 min (mean = 16.1 mm and CV = 55%), which represents between 0.2 and 86% of rainfall. Runoff variability was most likely related to differences in hydraulic conductivities and antecedent moisture conditions, despite the fact that the plots were prewetted. Infiltration rates are typically among the most variable soil properties with CV values of 23 to 97% (Jury et al., 2001). Likewise, a portion of the variability in runoff volume was probably due to leakage around the plot borders and runoff collection flumes, although care was taken to seal the borders and flumes.

In general, from plots with similar STP levels, runoff DRP concentrations were directly proportional to runoff volume. Pote et al. (1999b), who reported similar observations, suggested that high infiltration rates increased the transport of DRP into the soil where it is adsorbed resulting in lower DRP concentration from plots with lower runoff volume. Pierson et al. (2001) also observed this phenomena, and hypothesized that channelized flow may have played a role. The effect of

this channelized flow may have been to increase kinetic energy of flowing water, thereby enabling it to maintain a higher P concentration.

In an attempt to include the effect of runoff volume variability on the relationship between P in runoff and STP, we normalized P concentration in runoff between events by dividing by the amount of runoff (expressed as a depth on a plot area basis). When runoff P was normalized, its relationships with Mehlich III- and deionized water-extractable P improved. The strongest relationships between normalized runoff P and STP were between total P and deionized water-extractable P (Fig. 3) and DRP and deionized water-extractable P (Fig. 4). The effect was most pronounced with the 0- to 10-cm soil sample where r^2 increased from 0.58 (Table 3) to 0.84 (Fig. 3) for DRP and from 0.55 (Table 4) to 0.88 (Fig. 4) for total P. Pote et al. (1999b) reported that by normalizing DRP in runoff from three different soils, the relationship between deionized water-extractable P and DRP became the same for all three soils. They concluded that normalizing reduced the effect of differences in hydrology among soils on the relationship between STP and runoff P. In the present study, normalizing reduced the effect of hydrologic differences among different plots, all of which were the same soil series. Hydrologic differences at the plot scale used in this study could be due to many factors including differences in texture, structure, macroporosity, extent of ground cover, and microtopography, to name a few. In effect, differences in hydrology among sites may be controlling the effective depth and extent of interaction between runoff and the surface soil. The fact that the relationship between STP from the 0- to 10-cm samples and runoff P showed the most improvement indicates that in some

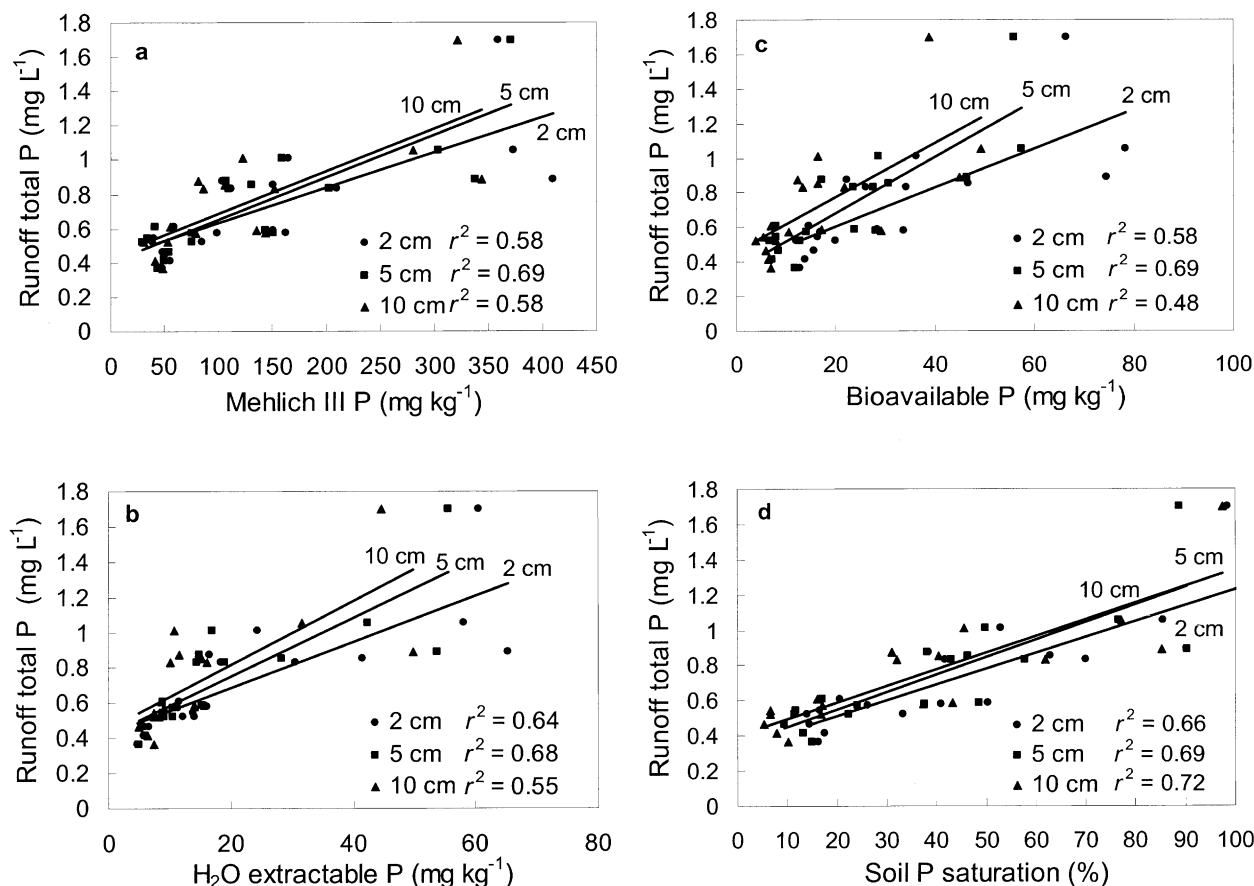


Fig. 2. Relationship between total P in runoff and four measures of soil P (Mehlich III, deionized water, Fe_2O_3 paper, and degree of phosphorus saturation [DPS]) from samples collected over three depths (0–2, 0–5, and 0–10 cm).

plots runoff is interacting with a greater depth of soil and by normalizing, the variability associated with these differences in interaction depth is reduced.

It is interesting to note that for total P and DRP, respectively, regression equations are similar for all STP methods (Table 4). The fact that there is little difference in the slope of the regression line between total P and DRP suggests that the relationship between STP and P in runoff may be independent of the form of the P in

the runoff. The principal difference between equations for total P versus DRP in the present study is the value of the intercept, which showed little variation with STP method or sampling depth but significant variation between total P and DRP. The difference between intercepts for total P versus DRP was due to the fact that total P values were generally larger than DRP values.

The Fe_2O_3 paper method of extracting P showed the weakest relationships with P in runoff. Only one of the

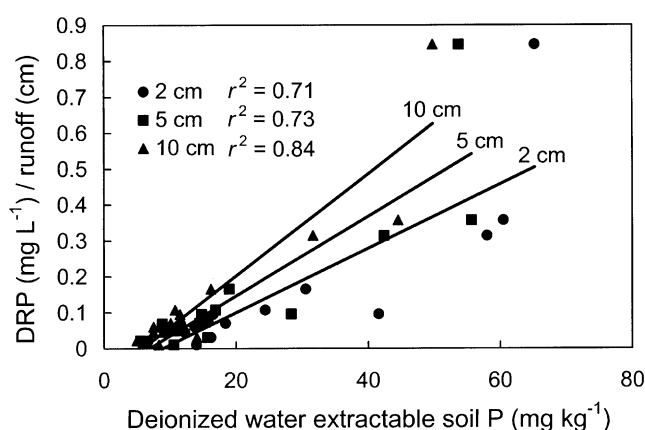


Fig. 3. Relationship between soil P extracted by deionized water and normalized (concentration divided by runoff depth) dissolved reactive phosphorus (DRP) in runoff.

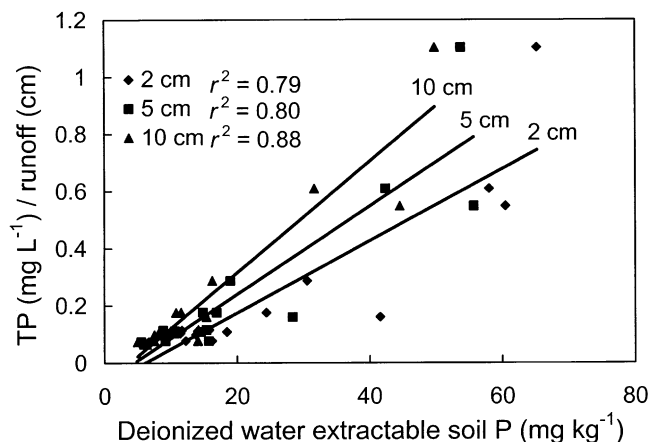


Fig. 4. Relationship between soil P extracted by deionized water and normalized (concentration divided by runoff depth) total P in runoff.

studies listed in Table 1 (Pote et al., 1996) reported on the relationship between Fe_2O_3 paper-extractable P and P in runoff ($r^2 = 0.81$). Since none of the fields in this study had received manure within one year, and in some cases not for several years, the Fe_2O_3 paper-extractable P in these soils may be less readily desorbed by runoff, leading to the weaker relationship reported in this study than in the study by Pote et al. (1996). In fact, the relationship between Fe_2O_3 paper-extractable P and runoff P was not significantly different from deionized water-extractable P. Given the amount of time required and the expense associated with the Fe_2O_3 paper method, it seems that there would be no advantage in adopting this method for studies involving highly weathered soils with sandy surface horizons such as those in this study.

Effect of Soil Sampling Depth

Most studies described earlier (Table 1) involve soil samples collected from a single soil depth (0–2 or 0–5 cm). The issue of sampling depth is important because there is a potential conflict between environmental sampling and agronomic sampling. Although STP levels were numerically different among the three soil sampling depths in this study, only the deionized water and Fe_2O_3 paper methods exhibited any statistically significant difference with depth (Table 3). The fact that there was little difference in extractable P with depth is reflected in the regression parameters listed in Table 4. Comparison of the slopes and intercepts of the regression lines for each combination of STP and depth versus P in runoff revealed that for all sampling depths there were no statistical differences between the slopes and intercepts ($p < 0.05$) for all measures of P in runoff. These results indicate that for the soil type and the depth ranges examined in this study, sampling depth may not have a significant effect on the relationship between STP and P in runoff. This is an important finding in light of producer concerns about the possibility that they may be required to collect soil samples for environmental analysis in addition to traditional agronomic samples.

Effect of Soil Series Variability

Closer scrutiny of the relationship between DPS and DRP in runoff (Fig. 2d) suggested the presence of clusters within the data. Analysis of these clusters revealed that there were indeed two significantly different groupings within the data (Fig. 5) consisting of nine plots in a lower cluster and eight plots in an upper cluster. There was one plot that did not fit into either cluster. The relationship between DPS and DRP was significantly stronger within clusters with 23 to 28% more of the variation in the relationship between DPS and DRP being explained when the groups were regressed separately (Table 5). Analysis of variance was used to determine if any soil properties were significantly different between the plots within the two clusters. The only difference between the plots in the two clusters was the ratio of Fe_{ox} to Al_{ox} . The upper cluster had an Fe_{ox} to

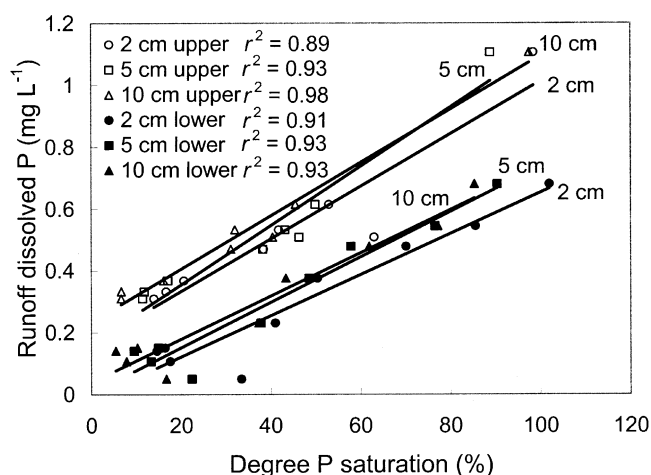


Fig. 5. Relationship between percent soil P saturation and dissolved reactive phosphorus (DRP) in runoff when sites are split into groups based on oxalate-extractable Fe to Al ratio.

Al_{ox} ratio of 1.5:1, and the lower group had a ratio of 1:1. Similar improvements in r^2 were seen between DRP and all other measures of STP when the data were split into the same groups. For the relationship between DRP and STP, splitting the data into groups affected the intercept of the regression equations but not the slope. The upper cluster had a significantly greater intercept ($p < 0.05$) than the lower cluster. This indicates that for a given STP level significantly more P may be lost in runoff from areas of a field with higher Fe_{ox} to Al_{ox} ratio. As with DRP, the relationship between total P and all measures of STP was improved by grouping plots based on Fe_{ox} to Al_{ox} ratio, although improvements were generally smaller. However, for total P, splitting the data affected the slope but not the intercept. For the total P regression equations, slope was significantly steeper in the upper cluster than in the lower cluster. The implication of the greater slope is that areas with larger Fe_{ox} to Al_{ox} ratio may produce proportionally greater P loss as STP increases than areas with lower Fe_{ox} to Al_{ox} ratio.

Differences in the ratio of oxalate-extractable Fe to Al in these soils could be a result of differences in parent material, management history, or some combination of these factors. Many fields in the Piedmont area of Georgia suffered from intense soil erosion as a result of cotton production during the first half of the 20th century. Many of these fields were terraced in the 1950s as a result of federal erosion control programs. Soil disturbance that resulted from the combination of erosion and terracing may be partially responsible for the Fe_{ox} to Al_{ox} ratio variability. However, there was no correlation between the Fe_{ox} to Al_{ox} ratio and any of the soil properties measured including thickness of the A horizon, which ranged from 7.5 to 28 cm. The fact that differences in Fe_{ox} to Al_{ox} ratio had a significant effect on the relationship between STP and DRP indicates that variability among soil properties within a soil series may limit the effectiveness of STP as a singular predictor of P loss potential.

When all plots were included, we were able to account

Table 5. Predictive equations and statistical parameters for the relationship between extractable soil P (mg kg⁻¹) and form of P in runoff when plots are clustered by Al to Fe ratio.

STP† method	Depth	Upper cluster			Lower cluster		
		Intercept	Slope	r ²	Intercept	Slope	r ²
	cm						
Relationship with runoff dissolved reactive phosphorus (DRP, mg L ⁻¹)							
Mehlich III	0–2	0.2201	0.0024	0.98	0.0475	0.0015	0.87
	0–5	0.2495	0.0023	0.99	0.0184	0.0019	0.91
	0–10	0.2468	0.0027	0.99	0.0422	0.0019	0.89
Deionized water	0–2	0.2050	0.0131	0.79	0.0921	0.0089	0.83
	0–5	0.2343	0.0151	0.89	0.0845	0.0116	0.81
	0–10	0.2480	0.0195	0.90	0.0763	0.0136	0.81
Fe ₂ O ₃	0–2	0.1550	0.0125	0.84	0.0364	0.0078	0.78
	0–5	0.1999	0.0149	0.93	0.0300	0.0112	0.78
	0–10	0.2083	0.0228	0.98	0.0660	0.0115	0.75
DPS‡	0–2	0.1643	0.0085	0.89	–0.0111	0.0066	0.91
	0–5	0.1642	0.0096	0.93	0.0004	0.0073	0.93
	0–10	0.2342	0.0086	0.98	0.0394	0.0070	0.93
Relationship with runoff total P (mg L ⁻¹)							
Mehlich III	0–2	0.4082	0.0036	0.98	0.3588	0.0016	0.88
	0–5	0.4513	0.0034	0.99	0.3302	0.0020	0.90
	0–10	0.0450	0.0040	0.97	0.3682	0.0019	0.80
Deionized water	0–2	0.3884	0.0193	0.78	0.4013	0.0097	0.87
	0–5	0.4317	0.0222	0.88	0.4043	0.0120	0.78
	0–10	0.4543	0.0285	0.87	0.4146	0.0130	0.65
Fe ₂ O ₃	0–2	0.3119	0.0185	0.84	0.3331	0.0088	0.86
	0–5	0.3787	0.0220	0.93	0.3210	0.0120	0.88
	0–10	0.3907	0.0338	0.98	0.3678	0.0120	0.82
DPS	0–2	0.3203	0.0127	0.91	0.3020	0.0070	0.88
	0–5	0.3193	0.0143	0.95	0.3272	0.0075	0.85
	0–10	0.4267	0.0128	0.99	0.3571	0.0073	0.89

† Soil test phosphorus.

‡ Degree of phosphorus saturation.

for 50 to 80% of the variability in P loss by relating STP to P in runoff. However, since we have shown that soil properties other than STP may influence this relationship (i.e., Fe_{ox} to Al_{ox} ratio), it seemed reasonable that by including some of these properties we could develop better overall P loss prediction equations. Therefore, multiple regression was performed with all forms of P in runoff against STP, pH, sand, clay, oxalate-extractable Al and Fe, ratio of Fe_{ox} to Al_{ox}, and total C for each soil sampling depth, landscape position, slope, and runoff volume. This process produced 24 unique equations with various combinations of the variables listed above and R² values of up to 0.91. Although there were differences among equations, STP (24 of 24), Al_{ox} (20 of 24), and Fe_{ox} (19 of 24) were included in almost all equations. There were some instances of autocorrelation among the variables used in the multiple regressions; however, Fe_{ox} and Al_{ox} showed no autocorrelation with any STP method or each other. Since Fe_{ox} and Al_{ox} were most consistently related to P in runoff, regression equations were developed using these two variables and STP for each runoff P versus STP combination. For all forms of P and all STP methods, R² increased with the inclusion of oxalate-extractable Al and Fe in the regression equation (Table 6). Interestingly, the coefficient on the Al_{ox} parameter was negative but the coefficient on the Fe_{ox} was positive, indicating that increased Al_{ox} would be associated with less P in runoff while higher levels of Fe_{ox} would indicate greater P loss. This is directly related to the effect of the ratio of Fe_{ox} to Al_{ox} discussed above. While studying the relationship between total soil P with P extracted by various STP ex-

tractants, Burt et al. (2002) reported a similar relationship between P_{ox}, Al_{ox}, and Fe_{ox} with P_{ox} being negatively related to Al_{ox} and positively related to Fe_{ox}. They reported that 79% of the variability in P_{ox} was explained when Al_{ox}, Fe_{ox}, and organic carbon were included in the regression equation. Agbenin (2003) reported that P sorption capacity of an Alfisol was strongly correlated to Al_{ox} but not to Fe_{ox}. Iron extracted from soils like Cecil and/or Madison by oxalate would mainly be associated with poorly crystalline iron oxides and hydroxides whereas oxalate-extractable Al could include exchangeable Al, poorly crystalline Al oxides and oxy-hydroxides, as well Al substituted into Fe oxides like goethite (Blume and Schwertmann, 1969; McKeague et al., 1971). Several researchers have reported that P sorption and desorption by goethite were related to the extent of Al substitution (Ainsworth et al., 1985; Peña and Torrent, 1990; Ruan and Gilkes, 1996). These researchers concluded that the principal effect of Al substitution was to increase the surface area of goethite and subsequently increase its P retention capacity. This effect of Al substitution on P sorption may help explain the fact that P in runoff was positively related to Fe_{ox} and negatively related to Al_{ox} in this study. The fact that the inclusion of oxalate-extractable Al and Fe improved the prediction of P loss is important because it may be one way to address the effect of the variability in soil series properties on the relationship between STP and P in runoff.

In light of the results of the present study, a closer review of the literature on the relationship between STP and runoff P may be revealing. All studies listed in Table 1 were conducted on small plots with established

Table 6. Multiple regression results for soil test phosphorus (STP) versus P in runoff.

STP method	Depth	Intercept	STP	Al _{ox} [†]	Fe _{ox} [†]	R ² initial [‡]	R ² final [‡]
cm							
Relationship with runoff dissolved reactive phosphorus (DRP, mg L ⁻¹)							
Mehlich III	0-2	0.50	0.0016	-0.00055	0.00015	0.56	0.75
	0-5	0.34	0.0020	-0.00051	0.00021	0.64	0.80
	0-10	0.47	0.0022	-0.00066	0.00023	0.58	0.81
Deionized water	0-2	0.53	0.0098	-0.00048	0.00008	0.65	0.78
	0-5	0.44	0.0136	-0.00056	0.00017	0.68	0.84
	0-10	0.46	0.0169	-0.00066	0.00024	0.58	0.82
Fe ₂ O ₃	0-2	0.53	0.0086	-0.00058	0.00012	0.54	0.69
	0-5	0.37	0.0126	-0.00052	0.00017	0.61	0.76
	0-10	0.56	0.0138	-0.00064	0.00015	0.44	0.69
DPS§	0-2	0.25	0.0069	-0.00037	0.00016	0.65	0.76
	0-5	0.11	0.0082	-0.00032	0.00022	0.69	0.80
	0-10	0.30	0.0075	-0.00043	0.00020	0.70	0.81
Relationship with runoff total P (mg L ⁻¹)							
Mehlich III	0-2	0.85	0.0020	-0.00061	0.00014	0.58	0.72
	0-5	0.53	0.0026	-0.00047	0.00024	0.69	0.78
	0-10	0.75	0.0027	-0.00069	-0.00024	0.58	0.74
Deionized water	0-2	0.88	0.0123	-0.00054	0.00005	0.64	0.75
	0-5	0.66	0.0170	-0.00053	0.00018	0.68	0.77
	0-10	0.76	0.0200	-0.00068	0.00025	0.55	0.70
Fe ₂ O ₃	0-2	0.88	0.0110	-0.00066	0.00010	0.58	0.74
	0-5	0.55	0.0166	-0.00047	0.00019	0.69	0.77
	0-10	0.86	0.0180	-0.00068	0.00015	0.48	0.64
DPS	0-2	0.52	0.0090	-0.00038	0.00015	0.66	0.73
	0-5	0.25	0.0104	-0.00022	0.00025	0.69	0.75
	0-10	0.53	0.0096	-0.00041	0.00021	0.72	0.78

[†] Al_{ox}, oxalate-extractable aluminum; Fe_{ox}, oxalate-extractable iron.

[‡] Initial regression model is simple linear regression of runoff P versus STP; final regression model is multiple linear regression where runoff P is related to STP, Al_{ox}, and Fe_{ox}.

§ Degree of phosphorus saturation.

sod covers and a single soil series, as were plots in the present study. However, in none of the previous studies were plots installed on more than one field with the same soil type. The fact that some soil properties (such as sand, clay, % C, Al_{ox} and Fe_{ox}, and Fe_{ox} to Al_{ox} ratio) varied considerably from plot to plot in the present study probably contributed to the weaker relationship between STP and runoff P described. The fact that normalizing DRP improved the relationship supports this conclusion because normalizing removes some of the variability associated with differences in hydrologic properties.

Effect of Recent Phosphorus Additions

In addition to soil variability there is evidence that residual manure P at the soil's surface may be a significant factor in the relationship between STP and P in runoff. Relationships between STP and DRP in runoff cited in Table 1 show a wide range of r^2 values (0.94–0.05), and there appears to be an inverse relationship between strength of the relationship and length of time since manure application. As the time since application increases the relationship seems to weaken. However, other researchers have reported a poor relationship between STP and P in runoff immediately following manure application (Eghball et al., 2002; Pierson et al., 2001). The implication of these findings is that the strength of the relationship between STP and P in runoff appears to increase for a period after manure application and then gradually decreases over several years. This effect may partially explain the lower r^2 values reported in this study since some fields had not received manure in several years. The effect of time since manure

application on the relationship between STP and P in runoff may be related to changes in the vertical distribution of P. When manure has been recently applied and not incorporated, there is a large pool of P that can contribute P directly to runoff. A soil sample tested immediately after manure application may not reflect the effect of the manure P if the P from the manure has not become incorporated into the soil. However, several months after manure application, manure P is more likely to be incorporated into the soil where it can be measured by a soil test and yet still be readily lost to surface runoff. The result is a strong relationship between STP and P in runoff. If, however, the situation is one where significant time has passed since manure application (several years), P extracted by a soil test may be more evenly distributed throughout the upper 5 to 10 cm resulting in less direct contact between extractable P and surface runoff. When the amount of contact between extractable P and runoff is reduced, the ability to predict one from the other may be reduced. Further research into the possible existence of a temporal effect is needed because of its potential implications for the use of STP for environmental purposes especially in the long-term prediction of P loss from soils with high STP levels where P application has been restricted.

CONCLUSIONS

This study differs from previous studies relating STP to runoff P from pastures and hayfields in that plots used in the present study were installed on more than one field and STP levels were not manipulated to achieve a predetermined range of STP values through

the addition of manure. In this study, we found a strong relationship between all STP methods and both total P and DRP in runoff. Positive relationships were found between DRP and all soil P test methods. Similar to Pote et al. (1996, 1999a, 1999b), we found that the strongest correlations to DRP in runoff were obtained with DPS. This relationship was strongest for the 0- to 10-cm sampling depth ($r^2 = 0.70$). It is important to note, however, that DRP and Mehlich III, at the 0- to 5-cm depth, were also correlated ($r^2 = 0.64$). With the exception of DPS, the strongest correlations between STP and runoff DRP were observed for soil samples collected from the 0- to 5-cm depth. Similarly, Torbert et al. (2002) reported that DRP in runoff showed the greatest correlation with Mehlich III- and deionized water-extractable P when soil samples were collected over the 0- to 5-cm depth. In general, from plots with similar STP levels, DRP concentrations were higher when runoff volumes were higher. Pote et al. (1999b), who reported similar observations, suggested that high infiltration rates increased the transport of DRP into the soil where it is adsorbed, resulting in lower DRP concentration from plots with lower runoff volume. Pierson et al. (2001) also observed this phenomena, and hypothesized that channelized flow may have played a role. The effect of this channelized flow may be to increase the kinetic energy of flowing water moving over the surface, thereby enabling it to maintain a higher P concentration.

Results of this study also indicate that the relationship between STP and P in runoff can be affected by variation in soil properties across sites within the same soil series. The principal effect of the variability across sites is variability in runoff volume. Normalizing runoff P concentration by runoff depth can reduce the effect of volume variability. We have also shown that inclusion of site-specific information about soil Al and Fe content can improve the relationship between STP and runoff P because within a soil series such as Cecil there may be areas where chemical or physical properties are sufficiently variable as to strongly affect the relationship between STP and runoff P. Finally, there may be a temporal component involved in the relationship between STP and runoff P in that as the time between manure application and the analysis of this relationship increases, the strength of the relationship decreases. Conversely, immediately after manure application there may be no relationship between STP and runoff P at all. These ambiguities may have implications for the use of STP in the prediction of runoff P. Further research into the temporal variability of the STP–runoff P relationship is needed, and it may be necessary to pursue a more mechanistic approach to the prediction of P loss.

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